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TITLE: $K^o_L \longrightarrow \mu\mu$ Polarization: Future Prospects

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$K_L^0 \to \mu\mu$ POLARIZATION: FUTURE PROSPECTS

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ABSTRACT

The observation of polarized muons in the final state of the decay $K_L^0 \to \mu\mu$ would be an indication of a new CP-noninvariant interaction. The theoretical literature describes a variety of physics mechanisms and many models in which such polarization may appear above the Standard Model background. We review this literature and describe experimental possibilities for carrying out the search for this polarization.

There is a great deal of activity in the field of rare kaon decays, as today's session indicates. These searches seek lepton-number-noninvariant processes, higher-order weak processes and new CP-noninvariant decays, among others. In particular, the search for CP-noninvariant processes beyond the mass-mixing-induced decays observed in the neutral kaon system has been stimulated by the results from NA31 and the interest in the b system. Today, I would like to point out the possibilities for observation of new CP-noninvariant mechanisms in the known decay $K_L^0 \to \mu\mu$. As many authors have pointed out,[1-8] any measurable polarization of the muons in the final state of this decay is a signature of a new physics process, one not included in the Standard Model. These processes involve CP-noninvariant mechanisms, though, as we shall see, in a bewildering array of models. I will briefly review this theoretical literature, and I will show how such an experimental search might be carried out, what studies we have done within the AGS experiment 791 collaboration, and what the future possibilities might be.

It was the community interest that I have sensed recently which motivated this talk. Work with the b system, the reports of a nonzero value for ϵ'/ϵ,[9] the several searches for the decay $K_L^0 \to \pi^0 ee$,[10] and discussions at BNL of searching for the decay $K_L^0 \to \pi^0 \nu\overline{\nu}$ [11] are important indicators. Think about that last experiment and you will appreciate that what I will describe today is comparatively simple! At conferences at which we have presented preliminary results of the work done in experiment 791, as in the previous discussion by John Urheim,[12] we have frequently been asked "Do you intend to search for $K_L^0 \to \mu\mu$ polarization?" The questioners undoubtedly know that this search was included in our original proposal and one might speculate that the question is motivated by genuine physics interest. That is probably the true motivation, but I cannot help wondering whether other, more prurient, interests are involved. I know more about this experiment now than when we wrote the proposal and I wonder whether these wise and knowing questioners ask this question more in the spirit of those who attend an auto race, not to see who is the winner, but in the hopes that they will be present during a wreck! I will try to indicate how difficult this measurement is likely to be, but I want to make sure to state clearly that within the experiment 791 collaboration we have no firm plan to carry out this search in the near future. I will tell you what is required, though, before such a search can be contemplated.

Figure 1 shows the leading diagrams for the known decay $K_L^0 \to \mu\mu$.[1] This process occurs principally by the higher-order induced strangeness-changing neutral currents involving exchanges of two photons, or an induced Z^0, or by the W box diagram. Prior to the current round of rare-decay searches, 27 events constituted the world sample,[13] with a branching fraction of $(9.1 \pm 1.9) \times 10^{-9}$, slightly above the lower bound set by unitarity considerations and the measured branching fraction for the decay $K_L^0 \to \gamma\gamma$.[13,14] More accurate measurements of the $\mu\mu$ decay rate might stimulate the theoretical community to produce more precise calculations which could then be used to constrain the quark mixing angles, the top-quark mass and new interactions. The really new physics, however, might come from the observation of muon polarization in this decay.

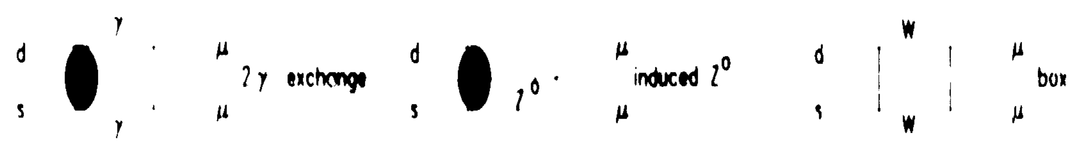

Fig. 1. Standard Model diagrams for the decay $K_L^0 \to \mu\mu$.

Though others wrote about this at an earlier time,[15] Herczeg really set the stage for this discussion within the modern Standard Model context.[1] As nearly as I can tell, all subsequent treatments of this subject depart from the ground laid out by Herczeg. Figure 2 illustrates the kind of "nonelectroweak" processes considered by Herczeg. All are outside the Standard Model. He constructs the matrix element for the $K_L^0 \to \mu\mu$ decay

$$M(K_L^0 \to \mu\mu) = a\overline{u}(p_-)\gamma_5 v(p_+) + ib\overline{u}(p_-)v(p_+) \quad , \tag{1}$$

where p_-, p_+ are the μ^- and μ^+ four-momenta, a is the CP-invariant ("old" physics) amplitude and b is the P- and CP-noninvariant ("new" physics) amplitude. He points out that, since the K_L is a linear combination of the CP-eigenstates K_2 and a small admixture of the CP-noninvariant state K_1, this mass-mixing can lead to a small polarization of the final state muons, which he calculates is

$$P = \frac{N_R - N_L}{N_R + N_L} \sim 7.1 \times 10^{-4} \quad . \tag{2}$$

This is the Standard Model "background." Any polarization larger than this must come from new physics processes.

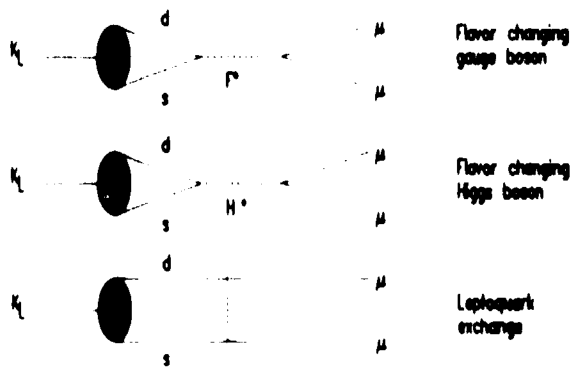

Fig. 2. Nonelectroweak diagrams for the decay $K_L^0 \to \mu\mu$.

Rewriting equation (1) in terms of the K_2 component of K_L alone, Herczeg gets

$$M(K_2 \to \mu\mu) = a_2\overline{u}(p_-)\gamma_5 v(p_+) + ib_2\overline{u}(p_-)v(p_+) \quad , \tag{3}$$

where a_2 and b_2 are the corresponding CP-invariant and P- and CP-noninvariant amplitudes. He shows that CP-noninvariance must be present for longitudinal muon polarization, getting

$$P = \frac{N_R - N_L}{N_R + N_L} = \frac{2r\,\mathrm{Im}(b_2 a_2^*)}{|a_2|^2 + r^2|b_2|^2} \quad . \tag{4}$$

For small polarization, this becomes

$$P \sim \frac{b}{a} \quad . \tag{5}$$

Thus, the polarization is proportional to the ratio of the new-physics amplitude and the old physics amplitude. If a search disclosed a polarization of 0.2, the new physics rate would be about 1% of the conventional rate. Since the known process appears with a branching fraction of $\sim 10^{-8}$, observation of a polarization of 0.2, quite feasible in several years, would amount to observation of a new rare process with a branching fraction of $\sim 10^{-10}$! That would be a very impressive "first"-generation rare-decay search.

Is there any reason to search for such polarization? Herczeg employs this framework to estimate the expected range of polarizations in the decays shown in Fig. 2. In the case of flavor-changing gauge-boson exchange, he derives a vanishing polarization. For flavor-changing Higgs exchange, however, the possibility is dramatically different. For a minimal Higgs model, where flavor is conserved and the couplings are Higgs to scalar, or in the case of an extra doublet where flavor is not conserved and the couplings are pseudoscalar, the polarization could be as large as unity, depending on mixing angles. Herczeg also shows such a large allowed range in the case of leptoquark exchange. In his framework, the suppressed Standard Model polarization and potentially large new-physics possibilities constitute an attractive "window" for the experimenter.

Chang and Mohapatra[2] extend this discussion by considering left-right symmetric models based upon $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, where right-handed currents allow CP-noninvariance even for only two generations and in which P- and CP-noninvariance are linked. Figure 3 illustrates a process of the type considered. Because the neutrinos change helicity, such models require massive neutrinos. These authors estimate muon polarizations in the range between 2 and 3×10^{-3}, slightly above the Standard Model background, but not measurable in the foreseeable future. They also estimate very small polarization in extended Higgs models.

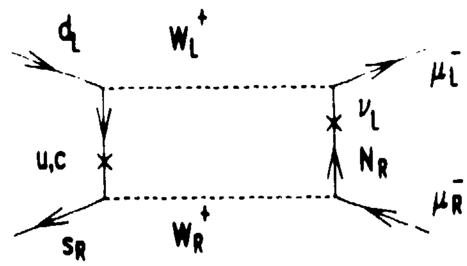

Fig. 3. A diagram for the decay $K_L^0 \to \mu\mu$ in a left-right symmetric model requiring massive neutrinos.

Botella and Lim[3] return to the flavor-changing Higgs exchange considered by Chang and Mohapatra and illustrated in Fig. 2. The previous authors derive very small polarization due to terms with high powers in the quark masses. Botella and Lim include terms linear in mass which can lead to high polarization if the Higgs is light or if there is an additional generation. They estimate polarizations as large as 0.96 if the Higgs mass falls in the range 325–477 MeV/c^2 or 517–4360 MeV/c^2. Similarly, if there is a fourth generation and the Higgs has a mass below 11.5 GeV/c, the polarization could be as large as 0.96.

Three papers consider models in which the polarization falls below the Standard Model level. Kurimoto[4] considers a supersymmetric model. In two different models, Liu[5] shows how an alternate choice of parameters lowers the expected polarization in Chang and Mohapatra's discussion, and in a superstring model,[6] Liu uses the current limit on the rare decay $\mu \to e\gamma$ to predict very small polarization.

Geng and Ng consider two models in which large polarization is possible. With CP-noninvariant[7] interactions involving flavor-conserving scalar-pseudoscalar mixing in interactions of nonminimal Higgs multiplets (two doublets plus a singlet), they estimate polarizations as large as 0.86. In a minimal charged-Higgs (two doublet) model,[8] retaining the Standard Model in other ways, and for scalars lighter than 5 GeV/c^2, they also get such large polarizations permitted.

I'm sure that I have not considered all the theoretical discussions of this subject, such as the left-right symmetric model of Frere presented at this conference. I apologize to anyone I inadvertently ignored. I have shown you, I expect, that there is a rich set of new physics possibilities which can be addressed in searches for this muon polarization. It is clear that observation of polarization significantly above the level of 10^{-3}, the Standard Model level, is another way to probe CP-noninvariance. The remaining questions are "How can such a search be accomplished?" and "What is the feasible sensitivity?"

In John Urheim's paper[12] you saw the experiment-791 two-arm spectrometer and its lepton identification systems. The muon rangefinder at the extreme downstream end of the system consists of 300 tons of Carrara marble plates, alternating with gaps which may be filled with drift tubes. In its use as a rangefinder, 13 gaps provide approximate 10% momentum-loss resolution. This system can be used as a muon polarimeter by filling all gaps with detectors. Using aluminum drift tubes, the entire system is constructed of material that does not induce significant depolarization of stopped positively charged muons. Negative muons capture and thus lose their polarization at their endpoints. The system is similar to, but less dilute than, the CHARM polarimeter,[16] which included plastic scintillation counters that disturb the polarization of muons stopping in the scintillators. The measurement principle is the well-known muon-spin-rotation technique,[17] in which a longitudinally polarized muon stops in a target and the decay positrons are detected by counters placed forward and backward to the incident muon track, surrounding the stopping point. Polarization results in an asymmetry between the forward and backward decay directions. In a proper experimental system, the stopping point is immersed in a transverse magnetic "guide" field, about which the stopped muon may precess. The forward-backward asymmetry is then measured in the rotating reference frame, which precesses about the stopping point. This sharply reduces the influence of systematic asymmetries. If the positron-decay time is recorded, as well as the direction, the data can be displayed in a way which measures the muon lifetime, providing another systematic check.

This type of detector is illustrated by Fig. 4, which shows a schematic of the test polarimeter[18] employed by us to validate the performance of our 300-ton system, prior to full construction. A carefully prepared beam of 130-MeV/c polarized positive muons from a LAMPF decay beam was stopped in the second of three marble absorber plates. The plates and the drift tube detectors, which alternated with the plates, were immersed in a 60-gauss transverse magnetic field. The stopped muons precessed with a period slightly longer than 1 μs. The decay positrons were detected in the drift tubes, which were recorded every 200 ns, for a period 6 μs before and after the muon stop time. Thus, the complete time history of the muon track and decay was recorded for approximately three muon lifetimes before and after the stop.

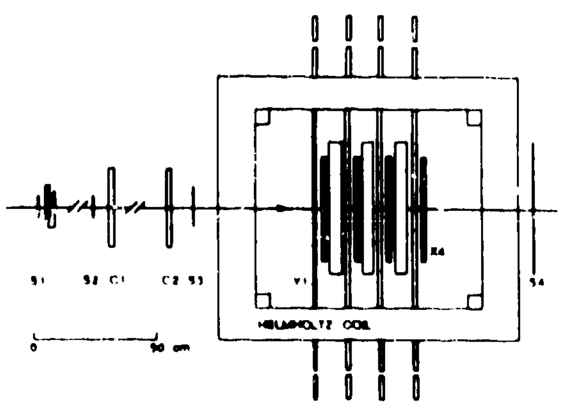

Fig. 4. Test polarimeter layout.

The incident muon-beam polarization was varied from nearly fully forward polarized, in the decay frame, to nearly backward polarized by varying the momentum of the upstream parent pions. The goal of this test was to measure the polarization analyzing power of such an instrument, at the expected incident muon rates in a full-scale experiment designed to have a sensitivity to polarizations as small as 15%. Data were collected for a variety of beam rates, polarizations, absorber-plate dimensions, and materials (aluminum and marble).

Figure 5 shows the raw time distribution in a plane of drift tubes. The muon lifetime is already evident in the slope, and the precession induced by polarization is evident in the slight periodicity with time. Most of the data are representative of the flat backgrounds associated with the incident beam passing through the system. Figure 6 shows similar data after simple spatial and time selections are made to reject the backgrounds. The muon lifetime is more evident. After a complete analysis, and subtracting upstream and downstream plane hits, the distributions of Fig. 7 are achieved. The periodicity of the polarization-induced precession is clear. The full analysis is described in Ref. 18. However, the measured analyzing power agrees well with predictions from design simulations. Since the detectors used are realistic examples of those used in the full system, and since the rates and backgrounds were also realistic, the design, which predicts sensitivity to 15% polarization with a raw sample of 10000 $K_L^0 \to \mu\mu$ decays, a sensitivity of $\sim 10^{-12}$, appears to be valid.

I have provided a theoretical motivation and described a proven technique by which the search could be carried out. So why haven't we used our detector to carry out the search? As you learned from John Urheim's paper, we have not yet achieved a sensitivity of 10^{-12}. The measurement requires 10000 $\mu\mu$ decays. Our current sample of 87 events is not enough. What are the prospects for the future?

Table I compares our 1984 design capability, and the recent concept discussed by the KEK E137 group.[19] I label this Table "Past Experimental Possibilities" since I do not intend to introduce new techniques, though these two groups, and any others, would have considerable design work to do before a new experiment is likely to be mounted. Thus, improvements might be achieved. The KEK estimate achieves

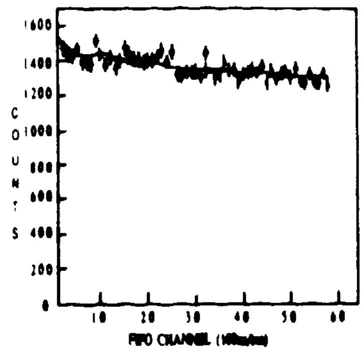

Fig. 5. Raw time distribution in a test-polarimeter detector plane.

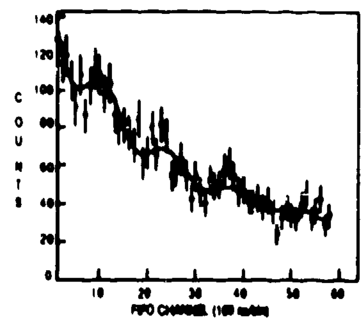

Fig. 6. Test-polarimeter-detector time distribution after simple spatial and time selections were made.

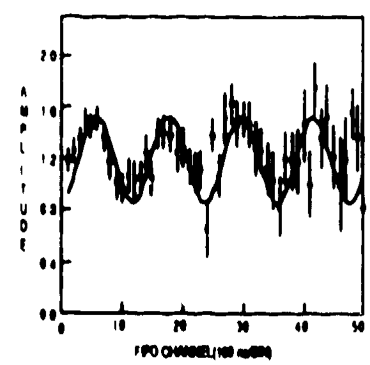

Fig. 7. Fully analyzed time distribution of the difference between upstream and downstream detector planes. For display purposes, the value in each bin was added to 1.0.

Table I. Past Experimental Possibilities

	E791 (1984)	KEK (TRIUMF Workshop 1988)
Raw events	10000	1000
Momentum	2–6 GeV/c	1–3 GeV/c
Stopping fraction	0.45	0.8
Time window	0.75	0.8
Positron efficiency	0.2	0.3
Analyzing power	0.3	0.3
Fully measured events	700	200
Sensitivity	14%	20%

sensitivity to 20% polarization with an order-of-magnitude fewer decays entering the detector. This is primarily due to the higher efficiency achievable in stopping the softer muons at the lower-energy KEK PS, with reasonable cost limits on the detector mass.

Collecting one thousand $\mu\mu$ decays at KEK is probably easier than collecting ten thousand at the AGS, given today's beam currents at these machines. With the AGS booster available in 1991, however, the two laboratories are more evenly matched, though the KEK version of the experiment is more compact and, therefore, more affordable. Both teams are collecting data this year, with sensitivities in the 10^{-11} range. Will they be able to achieve the necessary sensitivity improvement by a factor of about 100? Both experiments are currently running drift-chamber spectrometers at their rate limits. Both experiments will require substantially improved detectors, incorporating new technology. Dramatic improvements in geometric acceptance, and in rate-handling capabilities will be necessary. Such improvements are achievable, in my opinion. Scintillator detectors, and the technologies planned for use at the SSC, as well as new geometries, will be required. These experiments will be expensive by fixed-target laboratory standards. However, they will be capable of the full gamut of rare-kaon-decay research.

Let me close with a few remarks on the relative difficulty of various rare-kaon-decay searches in the next generation. Of the two-lepton final-state decays of the neutral kaon system, given adequate beam intensity, the easiest experiment to push beyond the 10^{-11} sensitivity range is the decay $K_L^0 \rightarrow ee$. Electron identification is simpler, backgrounds from the semileptonic decays are lower and the decay is kinematically separated from competing processes. Our extremely clean searches for this decay[12] are evidence for this. A search for $K_L^0 \rightarrow \mu\mu$, with background, is next in difficulty. Carrying out such a search with no backgrounds from semileptonic decays and from muon misidentification is still more difficult. At least this decay has a signal. To date, the decay $K_L^0 \rightarrow \mu e$ has yielded no signal, so it is a more difficult experiment to carry out a background free search. Finally, because of the fine sensitivity required, and the inefficiency in operating a polarimeter, the search for polarization in the decay $K_L^0 \rightarrow \mu\mu$ is most difficult. This is my point. For an experimental team contemplating a next-generation rare-kaon-decay effort, the polarization search is the most difficult. Unless one can approach this experiment with a frontal assault that can make a great leap in sensitivity across the board, the polarization search may not take place for awhile. The great leap forward may take place, though.

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